referred to as a **constant deviation** prism because the incident and emerging light rays wi be parallel, regardless of the angle at which light enters the prism. Porro prisms are often employed in traditional binocular configurations, where they are doubled together orthogon to first invert and then reverse light beams to produce erect or upright images. The twin prisms fold the light path of an optical system and also displace the image both horizontall\ and vertically by half the length of the hypotenuse in each direction. Binocular prisms are usually manufactured with rounded corners to reduce weight and size, and have a small sl cut into the hypotenuse face to obstruct light rays that are internally reflected at glancing angles.

A third orientation of the right-angle prism with respect to the incident light beam (Figure 2(is commonly referred to as a **dove** prism, which is useful as an image rotator. Dove prisms often have the unnecessary triangular apex section removed, both to save weight and to reduce stray internal reflections. A bundle of light rays enters the dove prism parallel to the hypotenuse face, and is refracted downward at the first leg toward the longer internal surfa Upon being totally reflected by the hypotenuse face, the light is then refracted again as it e the prism through the other leg and proceeds in the same direction that it was traveling bef entering the prism. Because the dove prism introduces a substantial amount of astigmatisr when convergent light is passed through, it is used almost exclusively with collimated light. The dove prism does not deviate or displace an image, but it can be utilized to either invert reverse an image.

Interactive Java Tutorial

Right-Angle Prisms
Discover how light reflection and rotation, inversion, and reversion of an image by a right-angle prism changes as a function of the prism orientation with respect to incident light.

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Although at first glance the dove prism appears to be a good candidate for dispersion (due the angular entrance of the light beam), transmission of light through the prism is actually equivalent to passage through a slab of glass with the side benefit of image rotation. An interesting effect of the dove-style geometry results as the prism is rotated along the longitudinal axis. In the orientation presented in Figure 2(c), light passing through the dove prism forms an image that is inverted from top to bottom and reversed from right to left. However, if the prism is rotated 45 degrees, the resulting image is rotated through 90 degrees, and when the prism is rotated another 45 degrees (for a total of 90 degrees, in effect, being placed on its "side"), the image is now rotated by 180 degrees. Thus, the ima(is rotated twice as fast as the prism. In practice, two dove prisms are often cemented toget at the hypotenuse (after placing a mirrored surface on these faces) to produce a bi-prism v the ability to change the direction of sight for telescopes, periscopes, and other optical instruments.

Right-Angle Prism Tunnel Diagrams

(a) Right-Angle Prism

(b) Porro Prism

(c) Dove Prism

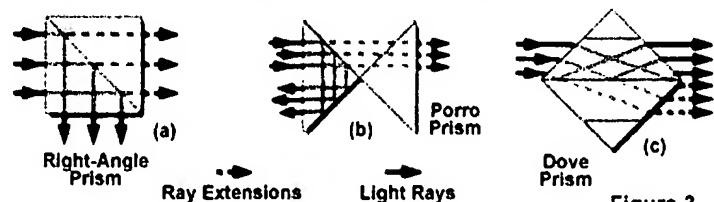Ray Extensions   Light Rays

Figure 3

Reflecting prisms can be represented as a plane parallel glass plate or block having a thickness that can be determined by unfolding the prism around its reflecting surfaces, as illustrated in Figure 3. Unfolded prisms are displayed in the form of a **tunnel diagram**, and have a thickness equal to the length of the entrance and exit faces. Armed with this information, the **apparent thickness** of a prism can be determined from the refractive inde which is expressed by the equation:

Apparent thickness = d/n

where **d** is the glass thickness (determined from the unfolded prism), and **n** is the index of refraction. The unfolded prism path for simple right-angle and Porro prisms is presented in Figure 3(a) and Figure 3(b), respectively. For a right-angle prism, the unfolded thickness equals the length of the short legs (through which light enters and exits the prism). Unfoldir prism will also demonstrate the maximum beam size that can pass through without spread past the edges of the prism. A tunnel diagram for the dove prism is illustrated in Figure 3(c and shows the unfolded path of refracted light rays as they would traverse a glass block tilt with respect to the incident light angle. Note that this configuration is the only prism in Figu that experiences refraction at the incident and exit interfaces. The angular entry of light ray into a dove prism requires that the height of the entrance face be limited by the length of th base (the hypotenuse, or long face). Unfolding the components of an optical system is ofte the best way to determine how light passes through the various apertures, lenses, and angular deflectors, which can be utilized to optimize design parameters and efficiency.

Replacing the hypotenuse face of a right-angle prism by a total internal reflection **roof**, consisting of two surfaces positioned at 90-degree angles with respect to one another, yiel an **Amici** prism (see Figure 4). Addition of the roof serves to maintain the 90-degree invers to the image observed with a right-angle prism, but also rotates the image by 180 degrees around the optical axis. At the roof surface, light rays incident at angles that would normall enable them to be transmitted through the hypotenuse face undergo crossover by total internal reflection through the prism. The result is to divide images in the center and transp the left and right portions. Amici prisms are expensive and difficult to fabricate because the roof angle must be held to a tolerance of 2-4 seconds of arc to avoid producing a double image artifact. In addition, introduction of the roof element degrades diffraction-limited resolution by almost a factor of two in the direction perpendicular to the roof edge, regardle of the accuracy of construction. This artifact can be partially offset by multi-layer coatings applied to the surface.

## Image Rotation, Deviation, and Displacement by Common Prisms

Figure 4

Penta Prism — 90° Deviation
Amici Prism — 180° Image Rotation
Rhomboid Prism — Lateral Image Displacement
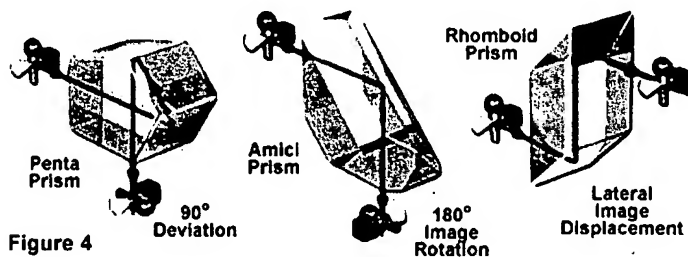
Another common design, the **penta** prism, deflects light through a constant 90-degree ang without reversing the image (this prism should not be confused with the more complex **pentaprism** utilized in single-lens reflex cameras, which also uses a roof prism to produce erect image). As illustrated in Figure 4, the penta prism reflects light from two internal surfa at angles insufficient to undergo total internal reflection, thus requiring thin external mirror coatings. Penta prisms are often referred to as an **optical square** (as applied to surveying instruments), because the incoming light beam is deviated at the same angle, regardless o the prism orientation with respect to the line of sight. **Rhomboid** prisms are made in the shape of a parallelogram to displace a light beam or the line of sight without affecting the orientation of the image (Figure 4). The prisms have two smaller parallel reflecting surfaces (legs) that are cut at a 45-degree angle to a much longer rectangular-shaped body. A varie of additional prism designs have unique properties, primarily image erecting and inversion, which enable them to perform specific functions in optical systems. For further information, reader is referred to advanced texts on the subject.

Polarizing Prisms

Scottish physicist William Nicol first devised a polarizing prism in 1828 by cutting a rhombohedral section of the mineral calcite (**Iceland spar**) diagonally, polishing the cut surfaces, and cementing them back together with Canada balsam. The result is a transpar

birefringent crystal, known as a **Nicol** prism, which effective separates polarized light at the interface between the two crystal halves. Upon entering the prism through one of the small angled legs (parallel to the long axis of the crystal), non-polarized light is split into two polarized components, termed the **ordinary** and **extraordinary** waves, which traverse the crystal at different speeds. The two separated light waves also have their electric vector vibration directions positioned at a 90-degree angle with respect to one another. When the interface between the two crystal sections is encountered by the separated light waves, the ordinary component is refracted to a much greater degree and is absorbed by a layer of bl; paint applied to the outer surface of the prism. In contrast, the extraordinary ray passes through the interface and emerges from the prism slightly displaced, but still traveling in a direction that is parallel to the incident light. The resulting plane-polarized light can be utiliz to illuminate birefringent specimens in a microscope or any other device that requires the input of light having electric field vibrations restricted to a single plane.

Common variations of the Nicol prism include the **Glan-Foucault** polarizer (See Figure 5), which consists of two identical prisms of calcite cut with the optical axes parallel to the corr edges, and mounted with a small air gap so that the long crystal faces are parallel to one another. This prism is transparent to wavelengths ranging from about 230 nanometers, in t ultraviolet region of the spectrum, to over 5000-nanometer infrared radiation. Such a broad wavelength range enables Glan-Foucault prisms to be utilized in a variety of instruments. L the Nicol prism, incident light striking the Glan-Foucault prism is separated into ordinary an extraordinary waves that are vibrating either parallel or perpendicular to the optical axis. However, in this case, the divided light waves travel through the prism without refraction ur they encounter the air boundary, whereupon the ordinary ray is totally internally reflected, t the extraordinary ray passes through the boundary with only a slight deviation.

Light Paths Through Polarizing Prisms

Figure 5
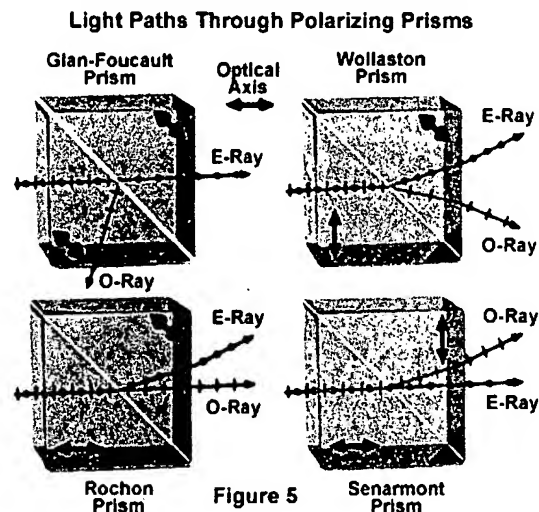
If the crystal halves are cemented together, the prism is then referred to as a **Glan-Thompson** polarizer (or prism), and can withstand more intense radiation, such as that fro high-intensity laser source. A third birefringent prism is known as the **Wollaston** prism, wh is really a polarizing beamsplitter made from two calcite or quartz sections cemented toget with the optical axes oriented orthogonally (Figure 5). Polarized light passing through a Wollaston prism is separated into orthogonal waves, as described above for the other polarizing prisms. However, when the ordinary and extraordinary waves encounter the diagonal cement junction, they exchange identities, are refracted in different directions, an emerge from the prism slightly displaced from one another. The deviation angle between tl two exiting light waves is determined by the wedge angle of the prism, which is usually var between 15 and 45 degrees.

Several derivatives of the Glan-style prisms can be produced by altering the orientation of calcite or quartz optical axes with respect to the individual crystal halves (Figure 5). The **Rochon** prism positions the axes orthogonally to each other and is arranged so that incide

non-polarized light enters the prism parallel to the optical axis (and is not separated). Whei light waves pass through junction in a Rochon prism, they enter a new region where the optical axis is oriented perpendicular to the waves. This causes the light to be split into ordinary and extraordinary components, with the ordinary wave passing through undeviate and the extraordinary wave being refracted away from the perpendicular. The reverse scenario can be achieved with a **Senarmont** prism, which also has the axis of the first crys section oriented parallel to incident illumination. However, when the light waves encounter boundary in a Senarmont prism (see Figure 5), the orientation of the optical axis in the sec half of the prism allows the extraordinary ray to pass through undeviated, but refracts the ordinary wave. These prisms can be utilized to select individual portions of polarized light f specific optical applications.

Refracting or Dispersing Prisms

The first demonstration of refraction and dispersion in a triangular prism was performed by British physicist Sir Isaac Newton in the late 1600s. Newton showed that white light could t dissected into its component colors by an isosceles prism having equal sides and angles. I general, a refracting or dispersing prism has two or more plane surfaces that are oriented i manner favorable to refraction rather than reflection of incident light beams. When a light ri strikes the surface of a dispersing prism, it is refracted upon entering according to Snell's l; and then passes through the glass until the second interface is reached. Once again, the li ray is refracted and emerges from the prism along a new path (see Figure 6). Because the prism alters the propagation direction of light, waves passing through a prism are said to b deviated by a specific angle, which can be very precisely determined by applying Snell's la to the geometry of the prism. The deviation angle is minimized when the light wave enters prism with an angle that allows the beam to traverse through the glass in a direction paralle the base.

Equilateral Dispersing Prism

Figure 6
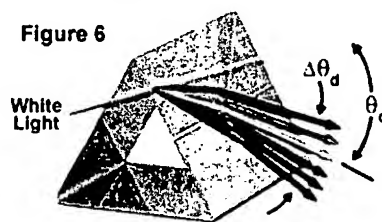
The amount of light deviation produced by a prism is a function of the incident angle, the prism apex (top) angle, and the refractive index of the material from which the prism is constructed. As prism refractive index values are increased, so is the deviation angle of lig passing through the prism. Refractive index is often dependent upon the wavelength of ligh with shorter wavelengths (blue light) being refracted at greater angles than longer wavelengths (red light). This variation of the deviation angle with wavelength is referred to **dispersion**, and is responsible for the phenomenon that Newton observed over 300 years ago.

Interactive Java Tutorial

Refraction by an Equilateral Prism
Discover how the incident angle of white light entering the prism affects the degree of dispersion and the angles of light exiting the prism. The tutorial also explores how changes in refractive index affect dispersion of light passing through the prism.

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Dispersion can be fine-tuned by selecting glasses with the appropriate refractive index characteristics for a particular application. In general, the dispersion properties of various

glass formulations are compared through **Abbe** numbers, which are determined by measu the refractive indices of specific reference wavelengths passed through the glass. Abbe numbers for popular glasses utilized in prism construction are listed in Table 1. As is evide from examining the table, lower Abbe numbers refer to higher dispersive power, translatin(into a greater angular spread of colors in the emerging light spectrum.

Abbe Numbers and Refractive Indices of Prism Glasses

Glass Formula	Refractive Index	Abbe Number
Fused Quartz	1.4585	67.8
BK 7	1.5168	64.17
Light Barium Crown	1.5411	59.9
Light Flint	1.5725	42.5
Dense Flint Glass	1.620	36.37
Extra Dense Flint Glass	1.6725	32.20
Very Dense Flint Glass	1.728	28.41

Table 1

The principal application for dispersing prisms is to separate wavelengths in the field of spectroscopy, which is concerned with the study and analysis of spectra. Although prisms were once the optical component of choice for spectrometers and spectrophotometers, diffraction gratings now command a leading role in these instruments. Gratings produce lin dispersion of white light rather than the complex angle versus wavelength relationship exhibited by prisms. However, prisms do have several advantages over gratings, including their enhanced power-handling capabilities, absence of unwanted higher order diffraction phenomena, and lower stray light.

Prism Materials and Manufacturing

In order for a prism to perform at the required specifications, it should be manufactured froi the correct glass formulation and be free from strain and internal defects. All surfaces of th· prism must be perfectly flat and ground to precise angles (although the angles in some pris are far more critical than others) deviating no more than 5 to 10 minutes for general use, bi held to just a few seconds for critical applications, such as roof prisms. Excess material at · corners is usually removed or chamfered in order to reduce chipping and cracking and to minimize the weight and size of the prism. External surfaces should be kept clean to the m exacting optical standards, which can be accomplished by applying a coat of lacquer or by silvering the surface where appropriate. In many instances, notches are milled across the surface to suppress ghost images produced by stray internal reflections.

Variations in glass density within the prism material can produce image distortion and alter dispersion characteristics of the glass. In a similar manner, bubbles or foreign debris in the glass can produce diffraction artifacts and reduce light transmission. Glasses chosen for pi construction are characterized by their refractive index, dispersion, and light transmission properties.

Beamsplitters

A beamsplitter is a common optical component that partially transmits and partially reflects incident light beam, usually in unequal proportions. In addition to the task of dividing light, beamsplitters can be employed to recombine two separate light beams or images into a sir path. The simplest configuration for a beamsplitter is an uncoated flat glass plate (such as microscope slide), which has an average surface reflectance of about 4 percent. When pla at a 45-degree angle, the plate will transmit most of the light, but reflect a small amount at 90-degree angle to the incident beam. **Plate** beamsplitters are, as the name implies, optica crown glass plates having a partially silvered coating designed to produce a desired transmission-to-reflection ratio. These ratios usually vary between 50:50 and 20:80, depending upon the application.
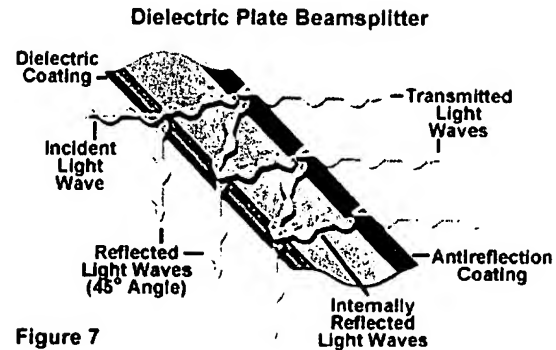
Dielectric Plate Beamsplitter

Figure 7

In general, a metallic or dielectric film is deposited on the **first** surface (facing the incident illumination) of the beamsplitter plate, while an antireflection coating is applied to the back (Figure 7). Antireflection coatings can be chosen to match the incident angle of light in orde to minimize the amount of light reflected from the rear surface of the plate and reduce the possibility of ghost images. Typical antireflection coatings display only about 0.5 percent reflectivity at an incident angle of 45 degrees. Dielectric coatings must also be fine-tuned t produce the proper reflectance, polarization properties, and wavelength distribution at the angle for which the beamsplitter is designed. Because both dielectric and antireflection coatings have negligible absorbance in the visible light region (typically 0.5 percent for a 5(beamsplitter at 45 degrees), plate beamsplitters are ideal for a wide spectrum of applicatio

One of the most serious consequences of using dielectric coatings for beamsplitter fabricat is the unequal transmission and reflection for **p** and **s** (parallel and perpendicular) polariza components of non-polarized incident light beams. As a result, some dielectric beamsplitte divide light unequally according to the polarization content, which can be undesirable in m; applications. When using dielectric coatings, this artifact can often be circumvented by alte the polarization vector orientation of the incident light. In addition, the polarization effect ca be reduced through the utilization of more sophisticated multi-layer thin-film dielectric coati designs, but often at the expense of other performance aspects.

Specialized non-polarizing beamsplitter coatings have been designed for use with polarize laser light where the incident radiation must maintain its polarization direction in both the transmitted and reflected beams. The coatings can effectively produce a clean 50/50 split c laser energy, regardless of the polarization state of the incident beam. As a side advantage non-polarized light incident on these coatings has both the parallel and perpendicular components transmitted at almost equal ratios. Plate beamsplitters can also be designed t act as longpass and shortpass edge filters (positioned at a 45-degree angle) for applicatior requiring specific wavelength selection. In the case of longpass filters, longer wavelengths transmitted and shorter wavelengths reflected at a 90-degree angle to the incident beam. Shortpass filters act in a reverse manner (transmit short wavelengths and reflect long wavelengths). Beamsplitters acting as edge filters are often referred to as **dichroic** or **dichromatic** mirrors.

Cube beamsplitters are fabricated by cementing together the hypotenuse faces of a match pair of right-angle prisms with a partially reflecting film deposited onto the face of one the prisms (Figure 8(a)). All four faces of a cube beam splitter are treated with an antireflection coating to minimize ghost images. For optimum results, the incident light beam should ente the beamsplitter through the prism that has been coated with reflecting film so that reflectic occurs before the beam encounters the optical cement used to glue the cube together. Cul beamsplitters are more resistant to mechanical damage and deformation than plate beamsplitters, primarily because the reflective surface is protected by being sandwiched between the glass prisms.
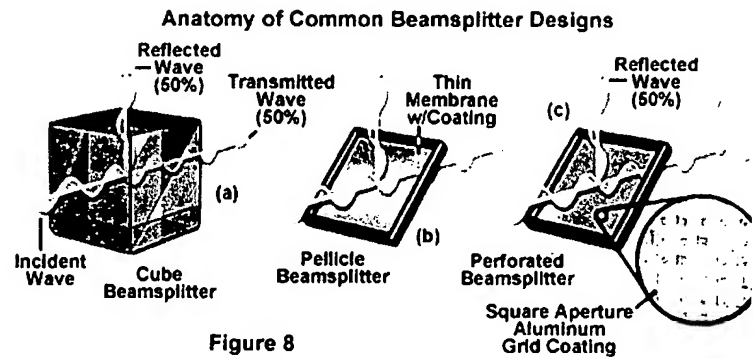
Anatomy of Common Beamsplitter Designs

Figure 8

Plate beamsplitters have some advantages when compared to cube beamsplitters, primari the lack of an optical cement in the vicinity of the dielectric or metallic film, which can absoi light energy and reduce transmission. As a consequence, plate beamsplitters can withstan significantly higher levels of radiation without suffering damage. Single glass plates are als much smaller and lighter than a twin-prism cube, and can be more easily fitted into tight spaces for compact optical configurations.

Advanced coatings for cube beamsplitters include hybrid metal-dielectric films that combin the benefits of both materials. The result is a moderately efficient broadband beamsplitter t typically has absorption levels of about 10 percent with very little polarization sensitivity. Absorption losses are almost equally divided between transmitted and reflected beams, an polarization components lie within 5 to 10 percent of each other. Other broadband coatings have lower absorption characteristics, but are extremely polarization sensitive. All-dielectri non-polarizing coatings are designed for high performance at specific wavelengths, usually laser applications.

A third important class of beamsplitters is fabricated from a high tensile strength elastic membrane (such as nitrocellulose) stretched like a canvas over a black anodized flat meta frame. Termed a **pellicle** beamsplitter (Figure 8(b)), the membrane thickness ranges betw 2 and 10 micrometers, so thin that it virtual eliminates ghost images. In addition, optical aberrations, such as chromatic, spherical, and astigmatism are reduced to a minimum whe compared to plate and cube beamsplitters, dramatically expanding the possibilities of usin convergent and divergent light. Uncoated pellicle membranes transmit about 92 percent of incident light throughout the visible and near-infrared spectral regions, but usually exhibit unacceptable absorbance in the ultraviolet. For most applications, pellicle membranes are coated with a thin dielectric film on the membrane side facing the incident light beam. Thes beamsplitters often fall victim to interference artifacts that result from the close proximity of membrane surfaces, and they can also be subject to acoustical vibrations. Pellicle membra surfaces should not be touched and can be cleaned only by a gentle flow of air.

Beam Steering by Wedge Prisms
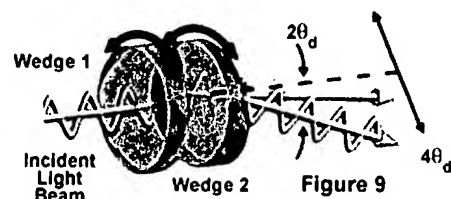
Figure 9

Perforated beamsplitters (often termed **polka-dot** beamsplitters; see Figure 8(c)) are fabricated by coating an optical glass substrate with a thin layer of aluminum in fixed-size square apertures. The resulting surface has a "polka-dot" appearance, thus the name. By carefully adjusting aperture size, the ratio of coated to uncoated surface area in a perforate beamsplitter can be manipulated to equally split incident beams into transmitted and reflec

components. Light waves encountering the uncoated surface pass through (losing a few percentage points to reflections from the glass) while those impacting the aluminum coatin are reflected (usually 45 degree angles). However, perforated beamsplitters demonstrate negligible sensitivity over a wide range of angles, and are useful for splitting light beams fr divergent, broadband radiant sources such as a mercury arc or tungsten-halogen lamps. Ir addition, the grid pattern displays insignificant divergence of the transmitted beam due to diffraction and does not suffer from polarization artifacts. These filters are also useful with deuterium and xenon lamps, and find applications in monochromators, spectrophotometef: and other optical systems.

Circular prisms having plane surfaces positioned at slight angles with respect to each othe are termed **optical wedges**, and deflect light by refraction rather than reflection. Although wedges are prismatic in nature, they can be manipulated to act as beamsplitters or **beam steerers**. The angle at which a wedge diverts incident light depends on the angle between entrance and exit faces and the refractive index of the glass utilized to manufacture the pla Wedge angles range between 2 and 25 degrees and have corresponding diopter powers between 2 and 20 centimeters deviation of the refracted light beam per meter of distance f the prism. The direction of light refracted after passing through the wedge can be controlle by rotating the circular prism (see Figure 9). In many cases, two wedges are paired and th light path is altered to an even greater degree over a 360-degree range by rotating the wedges in opposite directions. Wedge prisms act as versatile beamsplitters to prevent gho images and to steer light beams through adjustable pathways in optical systems.

Both prisms and beamsplitters are important components in microscope observation tubes where they act to steer light from the objective to the eyepieces or a camera port. In mode microscopes equipped with binocular eyepiece tubes, prisms are also utilized to change th line of sight direction from vertical to a more convenient 45-degree angle. Dichromatic beamsplitter mirrors are also important in fluorescence microscopy to provide excitation illumination for the specimen and to allow secondary fluorescence to enter the eyepieces while blocking reflected excitation wavelengths. Other optical instruments, such as telescopes, spotting scopes, and surveying transits also rely on prisms and beamsplitters t perform their functions.